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THE EQUIVALENT RECTANGLE IN PRESTRESSED CONCRETE DESIGN

By John J. Peebles, J. M. ASCE

STRUCTURAL DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

THE EQUIVALENT RECTANGLE IN PRESTRESSED CONCRETE DESIGN

By John J. Peebles,[1] J. M. ASCE

Synopsis

A simple procedure is presented for selecting cross-sectional shapes and dimensions for prestressed concrete beams in a manner similar to that used for selecting structural steel shapes. The required section modulus is computed from the bending moments and from the allowable working stress in concrete. From an equation utilizing an equivalent rectangular cross section, or by use of a chart, the dimensions of the selected shape can be determined rapidly.

Introduction

Prestressed concrete members differ from conventional reinforced concrete members in that compression is introduced into the member to counteract tensile stresses caused by the applied loads. Prestressed structures utilize more efficiently the compressive strength of concrete and the tensile strength of steel in the form of high-strength, cold-drawn wires or cables. As a result, much greater spans and load capacities are possible with prestressed concrete than would be feasible with conventional reinforced concrete. Thus, prestressing tends to place concrete in a much better competitive position relative to other structural materials.

One type of member that affords outstanding possibilites for economy of materials is the prestressed concrete beam. The most efficient cross section for this type of beam is usually an I, a T, or a hollow rectangle. These shapes do not lend themselves to rapid determination of cross-sectional properties such as areas and moments of inertia. Consequently, the design computations often become extremely tedious when the final dimensions for a given set of conditions must be obtained by assuming a series of trial sections.

Note.—Written comments are invited for publication; the last discussion should be submitted by October 1, 1953.

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Development of Basic Equations

Notation.—The letter symbols adopted for use in this paper are defined where they first appear, in the illustrations or in the text, and are arranged alphabetically for reference in the Appendix.

Rectangular cross sections lend themselves to a fairly direct method of design. For any given irregular-shaped section such as an I, a T, or a hollow rectangle, a solid rectangular section exists that is equivalent in area and moment of inertia about a given axis. This equivalent rectangle usually will have a height different from that of the actual section.

The basic design equation for prestressed concrete is of the form: $s = \frac{P}{A} \pm \frac{M\,y}{I}$, in which s is the unit fiber stress, P is the effective prestressing force, A represents the area of the gross concrete section, M denotes bending moment, y is the distance from the center of gravity of the gross concrete section (CGG)

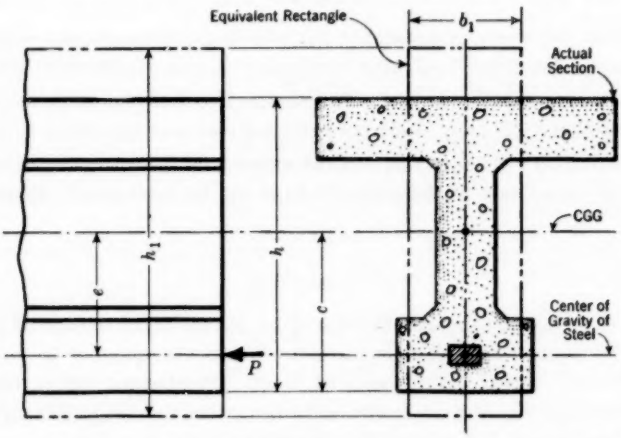

Fig. 1.—Relationship Between the Equivalent Rectangle and the Actual Cross Section.

to the fiber to be investigated, and I is the moment of inertia of the gross section about its center of gravity.

In the direct stress expression,

$$s = \frac{P}{A} \qquad (1a)$$

the stress depends on the force and the area only and is independent of the shape of the section. In the flexural stress expression,

$$s = \frac{M\,y}{I} \qquad (1b)$$

in which a straight-line variation is assumed, the stress is dependent on the shape of the section only insomuch as the moment of inertia and the fiber dis-

tance are dependent on this property. Therefore, the equivalent rectangle can be used as a basis for determining the required area and moment of inertia of the cross section, if coefficients are applied to the fiber distances to compensate for the differences in height.

Fig. 1 shows superimposed upon an I-section a rectangular section of height h_1 and width b_1, having a moment of inertia about the horizontal axis identical to that of the I-section and having the same CGG as has the I-section. The height of the actual section is h. The ratio of the bottom fiber distance to the height of the actual section may be expressed as

$$i = \frac{c}{h} \quad \ldots\ldots (2)$$

(For cross sections having horizontal axes of symmetry, $i = 0.500$.) Similarly,

$$i_1 = \frac{c}{h_1} \quad \ldots\ldots (3a)$$

and

$$i_2 = \frac{e}{h_1} \quad \ldots\ldots (3b)$$

The desired stress condition under full live load, all prestress losses having occurred, is that the bottom fiber stress equal zero. A step-by-step illustration of this appears in Fig. 2, in which compressive stresses are designated

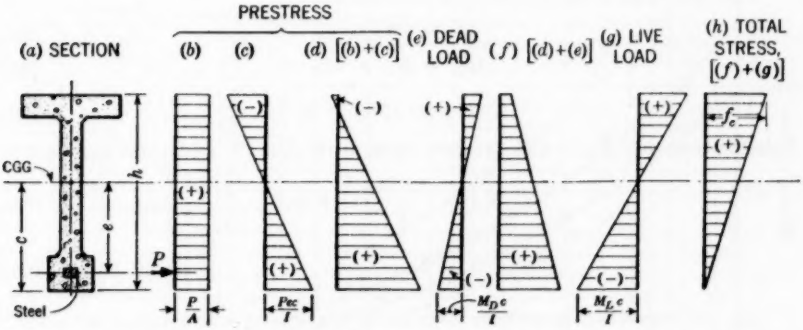

FIG. 2.—LONGITUDINAL STRESS DISTRIBUTION IN A PRESTRESSED CONCRETE I-SECTION

positive, and tensile stresses are designated negative. The desired bottom fiber stress is expressed as follows:

$$s = \frac{P}{A} + \frac{P\,e\,c}{I} - \frac{M_D\,c}{I} - \frac{M_L\,c}{I} = 0 \quad \ldots\ldots (4)$$

in which the subscripts D and L correspond to dead load and live load. Fig. 2 also shows that the direct stress portion of the prestress at the CGG is

$$\frac{P}{A} = \frac{c}{h} f_c = i f_c \quad \ldots\ldots (5a)$$

in which f_c is the working stress in concrete. Therefore, the equation for the prestress force is

$$P = i f_c A \quad \ldots\ldots (5b)$$

The area of the equivalent rectangle is expressed as

$$A = b_1 h_1 \quad \ldots\ldots (6a)$$

and, consequently,

$$P = i f_c b_1 h_1 \quad \ldots\ldots (6b)$$

The moment of inertia of the equivalent rectangle is

$$I = b_1 \frac{h^3_1}{12} \quad \ldots\ldots (7)$$

Substituting Eqs. 3, 6, and 7 into Eq. 4 and, reducing,

$$s = i f_c + 12 i f_c i_1 i_2 - \frac{12 M_D i_1}{b_1 h^2_1} - \frac{12 M_L i_1}{b_1 h^2_1} = 0 \quad \ldots\ldots (8)$$

It is emphasized that Eq. 8 shows the dimensions of the cross section to be independent of the properties of the steel prestressing wires and—for any given cross-sectional shape—to depend only on the bending moments and the allowable concrete working stress. Thus, the concrete sectional dimensions can be selected first, and the details of the prestressing steel can be determined later by using Eq. 5*b*.

The following equalities may be specified:

$$b_1 = z h_1 \quad \ldots\ldots (9a)$$

$$M_D + M_L = M_T \quad \ldots\ldots (9b)$$

and

$$i (1 + 12 i_1 i_2) = K \quad \ldots\ldots (9c)$$

Substituting into Eq. 8 the symbols defined by Eqs. 9, and collecting terms,

$$K f_c - \frac{12 M_T i_1}{z h^3_1} = 0 \quad \ldots\ldots (10a)$$

or

$$\frac{M_T}{K f_c} = \frac{z h^3_1}{12 i_1} \quad \ldots\ldots (10b)$$

Eq. 10*b* indicates the section modulus of the equivalent rectangular section. The required section modulus based on the total moment is Z_T, expressed as the quotient,

$$\frac{M_T}{K f_c} = Z_T \quad \ldots\ldots (11a)$$

and $h_1 = \frac{c}{i_1} = \frac{i h}{i_1}$. Therefore,

$$\left.\begin{aligned} Z_T &= \left(\frac{i^3 z}{12 i^4_1}\right) h^3 \\ \text{or} \qquad h &= \sqrt[3]{\left(\frac{12 i^4_1}{i^3 z}\right) Z_T} \end{aligned}\right\} \quad \ldots\ldots (11b)$$

Fig. 2 indicates that, if the ratio of live load to dead load is large, the live-load fiber stress may control the design. This fiber stress must not exceed the allowable working stress, f_c, because if it does, the bottom fiber stress will exceed f_c when the live load is not acting on the beam. In this case, the last element of Eq. 8, the expression $\frac{12\,M_L\,i_1}{b_1\,h^3_1}$ is equal to f_c. By the same procedure followed in arriving at Eqs. 11*b*, therefore,

$$\left.\begin{aligned} Z_L &= \left(\frac{i^3\,z}{12\,i^4_1}\right) h^3 \\ \text{or} \qquad h &= \sqrt[3]{\left(\frac{12\,i^4_1}{i^3\,z}\right) Z_L} \end{aligned}\right\} \qquad (12a)$$

in which

$$Z_L = \frac{M_L}{f_c} \qquad (12b)$$

In Eqs. 12*a*, Z_L is computed using the live-load moment and the working stress,

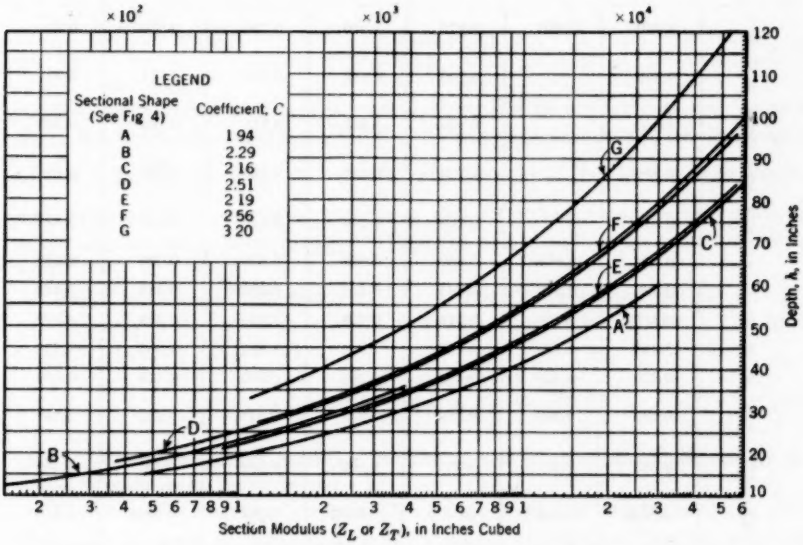

FIG. 3.—CHART FOR DETERMINING THE DEPTH OF THE CROSS SECTION

whereas Z_T in Eqs. 11*b* is computed using the sum of the dead-load moments and live-load moments and the working stress modified by the prestressing factor, K.

Fig. 3 is a chart based on Eqs. 11 and 12 for the various cross-sectional shapes shown in Fig. 4. The cubic equations for these shapes would be repre-

sented by parallel straight lines on logarithmic graph paper, but semilogarithmic paper was used so that the vertical scale would be uniform. Each curve is identified by its value of the coefficient $C = \sqrt[3]{\frac{12\, i^4_1}{i^3\, z}}$, as it appears in the

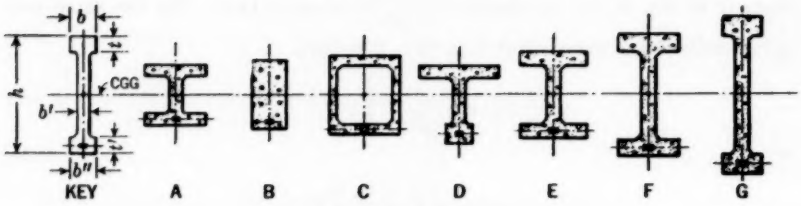

FIG. 4.—SECTIONAL SHAPES

TABLE 1.—SECTIONAL PROPERTIES[a] CORRESPONDING TO FIG. 4[b]

Geometric ratios	SECTION DESIGNATION IN FIG. 4						
	A	B	C	D	E	F	G
$\frac{b}{h}$	1.000	0.500	0.875	1.000	0.750	0.500	0.250
$\frac{b'}{h}$	0.200		0.100	0.167	0.143	0.111	0.091
$\frac{bt'}{h}$	1.000		0.100	0.333	0.750	0.500	0.250
$\frac{t}{h}$	0.200		0.125	0.167	0.167	0.143	0.125
$\frac{t'}{h}$	0.200		0.125	0.250	0.167	0.143	0.125
i	0.500	0.500	0.500	0.622	0.500	0.500	0.500
i_1	0.396	0.500	0.395	0.534	0.390	0.394	0.422
i_2	0.317	0.400	0.346	0.426	0.325	0.338	0.369
K	1.253	1.700	1.320	1.864	1.261	1.300	1.435
z	0.326	0.500	0.230	0.256	0.210	0.138	0.093
$\frac{A}{h^2}$	0.520	0.500	0.368	0.347	0.345	0.222	0.131
$\frac{w_D}{h^2}$	0.542	0.521	0.384	0.362	0.360	0.231	0.136
$\frac{I}{h^4}$	0.0690	0.0417	0.0492	0.0392	0.0475	0.0298	0.0153

[a] Properties of the equivalent rectangle also appear, and are defined by Fig. 1 and Eqs. 3, 6a, 7, 9a, and 9c. [b] The center of gravity of the steel (Fig. 4, Key) is at the center of gravity of the bottom flange.

equation, $h = C\sqrt[3]{Z}$, in which Z is either Z_L or Z_T as they are expressed in Eqs. 11 and 12.

The best procedure for determining the required cross-sectional dimensions is to obtain the value of h from Fig. 3, based on the live-load section modulus,

Z_L. Using this h-value for computing the first trial dead-load moment, h is again determined from Fig. 3, based on the total load section modulus, Z_T. Usually one or two adjustments of the dead-load moment will result in the correct section for the latter case, which is the same procedure used in the selection of structural steel shapes. The larger h-value based on either Z_L or Z_T governs the design.

When the depth h is controlled by the live-load section modulus, the eccentricity of the prestressing steel, e, must be reduced from that used on the chart to prevent overstressing by the prestressing force, P. Thus,

$$K f_c - \frac{M_T}{Z_L} = 0 \quad \ldots\ldots (13)$$

The required K-value is given by $K = \frac{M_T}{f_c Z_L}$; so that, using Eq. 9*c*,

$$i_2 = \frac{K - i}{12\, i\, i_1} \quad \ldots\ldots (14)$$

Using the relationships, $e = i_2 h_1$ and $h_1 = \frac{i h}{i_1}$, which were indicated previously, it is found that

$$e = \left(\frac{K - i}{12\, i^2_1}\right) h \quad \ldots\ldots (15)$$

The eccentricity of the prestressing wires can be adjusted at any section along the beam to compensate for the difference in moment by multiplying e by the ratio, $\frac{M_x}{M_T}$, in which M_x and M_T are the sum of the dead-load moments and live-load moments at a distance x along the beam and at the point of maximum moment, respectively. Thus, the eccentricity over the supports is zero.

Based on the four elements of Eq. 4, fiber stresses can be checked for conformance with design specifications in the intermediate stages. The fiber stress is expressed as follows:

$$s = i f_c \mp \frac{(i f_c A)\, e}{Z} \pm \frac{M_D}{Z} \pm \frac{M_L}{Z} \quad \ldots\ldots (16)$$

in which Z is the section modulus for the top or bottom fiber, depending on which fiber is to be investigated.

Theoretically, the fiber stresses should be checked on the basis of the area of the net concrete section, A_c, and the moment of inertia of the net concrete section, I_c. These properties and those of the transformed section can be computed at the designer's option after the sectional shape and dimensions have been determined. However, the usual design assumptions and the inherent inconsistency of concrete render questionable the justification for such refinements.

Referring to Fig. 4, theory and practice support the indication that a decrease in the depth of the section is accompanied by an increase in the required

area. Conversely, the deeper the section, the smaller the required area. Thus, a sectional shape may be chosen from a purely economical standpoint. For example, in a multistory building, although shallow beams will be more costly in themselves than will deep beams, the possibility for savings in the total height of the building may be a consideration.

In the case of bridges, overpasses, and similar structures, headroom may be an important consideration and the most shallow practicable beam may be desirable. However, in many situations headroom is not a governing factor, and the most economical beam can be utilized. Also, cases occur in which these two extremes must be balanced against each other and some average section may be desired in which each condition is partly satisfied.

Although economy apparently favors deeper beams, considerations of practicability tend to limit the depth. Tensile stresses in the top fibers of the beam over the supports (where the bending moments become zero) increase with increased depth of the beam. Provisions must be made to resist these stresses regardless of the shape of the beam, but the cost of such provisions increases with increased depth-span ratio of the beam. Also, deep, thin sections exhibit an increased tendency toward buckling, and more web stiffeners therefore are required. The seven shapes shown in Fig. 4 probably will cover most design conditions, but the variety of shapes that could be used is unlimited.

Eqs. 11 and 12 can be developed for other shapes, and curves can be drawn in the same manner as those in Fig. 3. In determining the various properties for the shapes shown in Fig. 4 (as listed in Table 1), the first step was to assume the flange and web proportions as some fraction of the height, h. These appear as the first five lines in Table 1. To avoid complicated algebraic expressions, actual dimensions of typical sections were used to determine the center of gravity of the section and to compute values of the area and of the moment of inertia about the horizontal axis through the CGG. Next, the dimensions of the equivalent rectangle were determined from Eqs. 2, 3*a*, 6*a*, and 7.

The center of gravity of the prestressing steel was assumed to be at the center of gravity of the bottom flange, and thus i_2 was some fraction of i_1. (The value of i_2 is different if the live load controls the design, but this fact does not affect the preparation of the curves.)

Eqs. 9*a* and 9*c* were used in evaluating K and z. Values for A and w_D in terms of h^2, and of I in terms of h^4, also were determined in order to facilitate rapid computation of these properties when h is known.

Examples

To illustrate the use of the equivalent rectangle in designing prestressed concrete beams, two examples are presented. Table 2 shows the initial steps in the computations. For the 100-ft span, a value of Z_L is found by dividing values in Col. 2 by those in Col. 3. Entering Fig. 3 with a value for Z_L yields and h-value of 41.1 in., which is used to compute the first trial value for Col. 8. The value of Z_T is obtained from Eq. 11*a*. Re-entering Fig. 3 with the value from Col. 9, an h-value of 47.4 in. is obtained, which does not agree with the value in Col. 6. A second trial value of h equal to 52 in. yields the values:

M_D = 11,700 kip-in. and M_T = 19,200 kip-in. The new value for Z_T is 8,200 in³. Using this value, a depth of h = 51.6 in. is obtained from Fig. 3. This is satisfactory.

Eq. 16 is used to check fiber stresses, yielding a top fiber stress of 1,800 lb per sq in. and a bottom fiber stress of 0 lb per sq in. Eq. 5*b* yields a prestressing force P equal to 532 kips.

TABLE 2.—COMPUTATIONS FOR PRESTRESSED BEAMS (FIRST TRIAL)

Span, in feet	$M_L \times 10^{-3}$, in kip-inches	f_c, in lb per sq in.	Shape (Fig. 4)	Z_L, in inches cubed	Depth,[a] h, in inches	Trial[b] $M_D \times 10^{-3}$, in kip-inches	$M_T \times 10^{-3}$, in kip-inches	Z_T, in inches cubed
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
100	7.500	1,800	F	4,160	41.1	7.330	14.830	6,350
40	4.800	2,250	D	2,135	32.3	1.131	5.931	1,413

[a] From Fig. 3. [b] The trial dead-load moment equals $w_D L^2/8$, plus 25% for the deck, stiffeners, and other components.

The required area of steel depends on the tensile strength of the wires or cables to be used. Fiber stresses in the concrete also can be checked using the initial prestressing force required to compensate for the subsequent prestress losses of approximately 15%.

For the 40-ft span, the Z_T-value in Col. 9, Table 2, is less than the value of Z_L in Col. 5, indicating the h-value of 32.3 in. (Col. 6) to be satisfactory. Thus, the live load controls the design and a new value of e must be obtained. Introducing values from Table 2 into Eq. 13 gives a K-value to be substituted into Eq. 15. The eccentricity is 5.79 in., the top fiber stresses are found to be 2,250 lb per sq in., and the bottom fiber stresses vanish. The required prestressing force is P = 507 kips.

CONCLUSIONS

A method has been presented whereby the shape and dimensions of regular and irregular cross sections of prestressed concrete beams can be determined rapidly in the same manner as that used for selecting structural steel shapes. The method has the following advantages:

(*a*) The time-consuming method of selecting trial sections and then checking the stresses is eliminated.

(*b*) The method is not limited to any particular sectional shapes.

(*c*) No complicated equations are involved.

(*d*) The method is particularly helpful to those who have had little or no previous experience in the design of prestressed concrete beams and thus have no basis for selecting trial sections.

(*e*) When making economic comparisons of beams of various materials, the quantities for the prestressed concrete beam can be determined quickly with the assurance that the stress conditions in the beam will be satisfactory under the given loading.

The method has the following disadvantages:

I. If sections other than those shown in Fig. 4 are used, the designer must formulate Eqs. 11 and 12 in order to determine the dimensions.

II. The required height of the section, h, may not be controlled by the sum of the dead-load moments and live-load moments, but may be controlled by the live-load moment alone—a situation which entails two computations for h.

APPENDIX. NOTATION

The following symbols, adopted for use in the paper and for the guidance of discussers, conform essentially with "American Standard Letter Symbols for Structural Analysis" (ASA–Z10.8–1949), prepared by a committee of the American Standards Association with ASCE participation, and approved by the Association in 1949:

A = the area of the gross concrete section;

A_c = the net area of concrete;

b = the top flange width:

b' = the web thickness;

b'' = the bottom flange width;

b_1 = the width of the equivalent rectangle;

C = the coefficient in the equation, $h = C Z^{\frac{1}{2}}$;

c = the distance from the CGG to the bottom fiber;

e = the eccentricity of the steel area with respect to the CGG;

f_c = the allowable working stress in concrete;

h = the height of the actual section;

h_1 = the height of the equivalent rectangle;

I = the moment of inertia of the gross concrete section referred to the CGG;

I_c = the moment of inertia of the net concrete section about its centroidal axis;

i = the ratio of the bottom fiber distance to the height of the actual section:

i_1 = the ratio of the bottom fiber distance of the actual section to the height of the equivalent rectangle;

i_2 = the ratio of the steel eccentricity to the height of the equivalent rectangle;

K = a prestressing factor;

L = the span;

M = the bending moment:
- M_D = the dead-load moment;
- M_L = the live-load moment;
- M_T = the total moment;

P = the effective prestressing force;

s = the unit stress;

t = the top flange thickness;

t' = the bottom flange thickness;

w_D = a uniform dead load;

x = the horizontal distance along a beam;

y = the vertical distance from the CGG;

Z = the section modulus:
- Z_L = the section modulus based on the live-load moment;
- Z_T = the section modulus based on the total moment; and

z = the ratio of the width of the equivalent rectangle to its height.

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